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Transmission filters for U.H.F. relay stations

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TRANSMISSION FILTERS FOR U.H.F. RELAY STATIONS

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Summary

Some designs of filter are reviewed and one particular type suitable for use at u.h.f. relay stations is considered in more detail.

Issued under the authority of

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Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

(RA-107)

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1. Introduction

Transmitters normally generate at low level frequencies other than those that it is intended to radiate. The frequencies of some of these components bear a simple harmonic relationship to the wanted frequency and may be suppressed to the desired degree fairly easily. More difficult are those frequencies that are generated by odd-order non-linearity in the amplifying stages of the transmitter since they lie close in frequency to the wanted signals, so that any measures taken to suppress them may result in distortion. The work described in this report was undertaken because it was desired to transmit television signals in Channel 21 (470 – 478 MHz) without causing interference to nearby mobile communication services operating in the frequency range 465 – 467 MHz. Television relay stations usually operate with common amplification of vision and sound signals so that third-order non-linearity of the common amplifier will give rise to image sound and image colour subcarrier components at 465·25 MHz and 466·82 MHz respectively; these are the components it was desired to attenuate,

The work was undertaken partly to review different types of filter and partly to provide filters for an experiment carried out at the Halifax relay station. In this experiment test transmissions were radiated on Channel 21 with a high degree of vestigial side-band suppression in order to determine whether nearby mobile communications services could be protected.

In general, the required characteristics could have been obtained with either band-pass or band-stop filters. However it is easier to obtain a very high attenuation over a narrow band of frequencies, together with a low attenuation at a nearby frequency, by means of a band-stop filter[1] and attention will be concentrated on this form.

2. Resonators derived from waveguides

2.1. The resonant cavity

Propagation in a waveguide is governed by the relation

$$\frac{1}{\lambda_g^2}+\frac{1}{\lambda_c^2}=\frac{1}{\lambda_o^2} \qquad (1)$$

where λ_o is the free-space wavelength
λ_g is the wavelength along the direction of propagation, Z,
λ_c is the wavelength in the direction normal to Z

If λ_c is fixed, then as λ_o is increased λ_g also increases, becoming infinite when $\lambda_o = \lambda_c$. Thus the guide has a cut off wavelength, λ_c.

If propagation in the Z direction is interrupted by a perfectly-reflecting wall, standing waves will be set up. If two such walls are introduced a cavity is formed which will be capable of sustaining a resonance if the spacing between the walls, z, is an integral number of half-wavelengths. Putting this condition in Equation (1) we have

$$\frac{1}{\lambda_o^2}=\frac{1}{\lambda_c^2}+\left(\frac{m}{2z}\right)^2 \qquad (2)$$

where m is an integer.

Resonant modes of oscillation can exist in any cavity bounded by perfectly-reflecting walls, no matter what its shape, but it is convenient to think in terms of those formed from commonly used types of waveguide. For example, a rectangular waveguide appropriate to frequencies just below 470 MHz would have interior cross-sectional dimensions of 457·2 mm x 228·6 mm. The minimum length for resonance at 465·25 MHz would be 342·2 mm.

Now the Q of a transmission line used as a resonator may be expressed in terms of the propagation constant, $\alpha + j\beta$, where α is the attenuation in Nepers and β the phase retardation in radians per unit length. If a length $n\lambda/4$ is used as a resonator then

$$Q = \beta/2\alpha \qquad (3)$$

irrespective of n provided that loss in the short circuit or short circuits is negligible. This result also applies when a length other than $n\lambda/4$ is used (e.g. when the line is tuned with an external loss-less capacitor) provided that the loss is caused by series resistance, dielectric loss being negligible.

It is more convenient to express Equation (3) in the form

$$Q=\frac{27{\cdot}29}{\text{Attenuation in dB per wavelength}} \qquad (4)$$

Returning to our example, the theoretical attenuation of the waveguide when constructed of aluminium is 0·152 dB/100 m corresponding to 0·00139 dB at a frequency of 465·25 MHz. Thus this resonator will have a Q of about 20,000.

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In this context, Q should be defined more precisely as the 'unloaded Q' or Q_u, being a function only of the cavity and the materials of which it is constructed.[2] When a cavity is coupled into a practical circuit it is damped by this circuit and the tighter the coupling the greater the damping. Any practical measurement will yield a value for the loaded Q or Q_L and to derive Q_u from measurements it would be necessary to make a series of measurements of Q_L with different degrees of coupling and then extrapolate to zero coupling. A convenient method of determining Q_L is by measurement of the 3 dB bandwidth of the response from which

$$Q_L = \frac{\text{Resonant frequency}}{\text{3 dB bandwidth}} \tag{5}$$

When a resonant cavity is used as a band-pass filter and is loaded equally by matched input and output lines, the values of loaded and unloaded Q may be related to the insertion loss L at resonance[2]

$$L = 20 \log_{10} \left(1 + \frac{Q_L}{Q_u}\right) \tag{6}$$

It may be seen that although cavity resonators give high values of Q_u they are somewhat bulky devices. Furthermore this size precludes a number of such resonators being used together in the way which, it will be seen later, is possible with coaxial and strip-line resonators. This means that all the required attenuation must be obtained in a single unit and it is impossible to control the shape of the attenuation curve as a function of frequency, other than by introducing external damping.

2.2. The rhumbatron[2,3,4,5]

If a cylindrical cavity is made re-entrant so that the capacity between the ends is increased the resonant frequency is lowered. Alternatively a smaller resonator may be obtained at a given frequency. This arrangement is known as a rhumbatron; it was originally devised for use with early types of klystron. In the limit, as the cavity is made more and more re-entrant, the device becomes a quarter-wave coaxial line short circuited at one end.

An experimental rhumbatron was made in copper with soft-soldered joints as shown in Fig. 1, the design being derived from Reference 5. The resonator was energised by means of small loops attached to coaxial connectors. The value of Q_u estimated from Reference 5 was 14,000 but a measurement of the band-pass response gave a minimum insertion loss of 1·6 dB and a Q_L of 358 at a frequency of 465 MHz. This indicated that Q_u was only about 2000, this low value presumably being attributed to additional losses inherent in the construction. The use of small coupling loops would have given a higher value of Q_L but would also have increased the insertion loss.

In order to realise a band-stop characteristic the rhumbatron was mounted on a rigid coaxial line so that the cavity could be coupled directly into the line. Fig. 2 shows the arrangement. With this design the adjustments for resonant frequency and for degree of coupling are interdependant but some control of the coupling may be effected by varying the diameter of the coupling hole (iris). The following results were obtained.

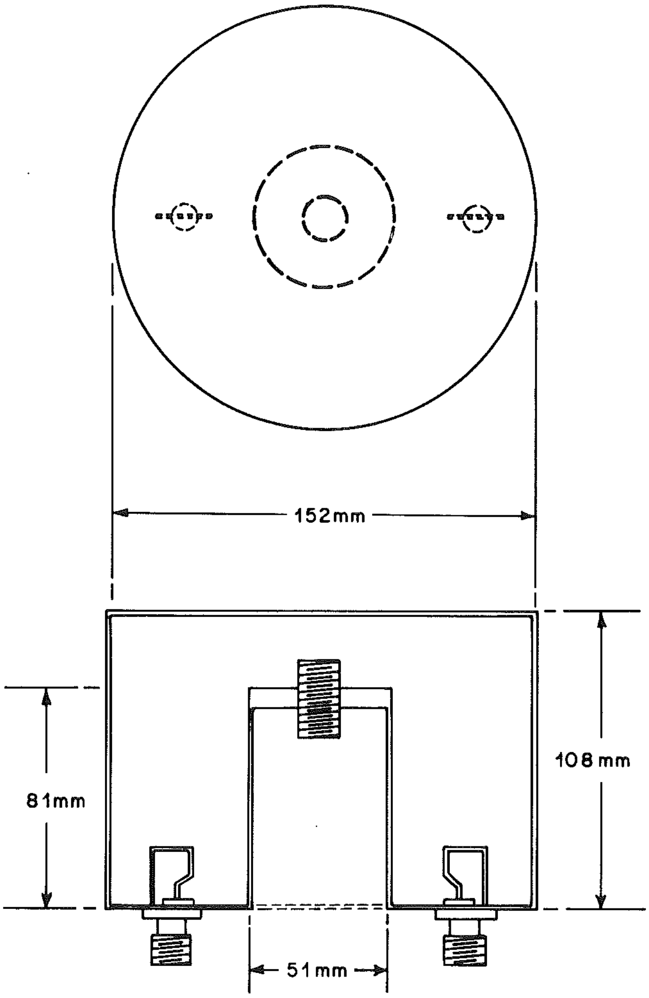

Fig. 1 - Rhumbatron band-pass resonator

With 19 mm diameter iris, maximum attenuation of 24 dB at 465 MHz with $Q_L = 465$

With 12·7 mm diameter iris, maximum attenuation of 20 dB at 465 MHz with $Q_L = 930$

These results are consistent with a value of Q_u of 7,000 – 8,000. A photograph of the rhumbatron is shown in Fig. 3 and both methods of energising it may be seen.

Although the rhumbatron is considerably smaller than the corresponding waveguide resonator, it still does not lend itself to combinations of units as readily as some truly coaxial units which will now be considered.

3. Resonators derived from coaxial lines

If a coaxial line has a resonant line section connected

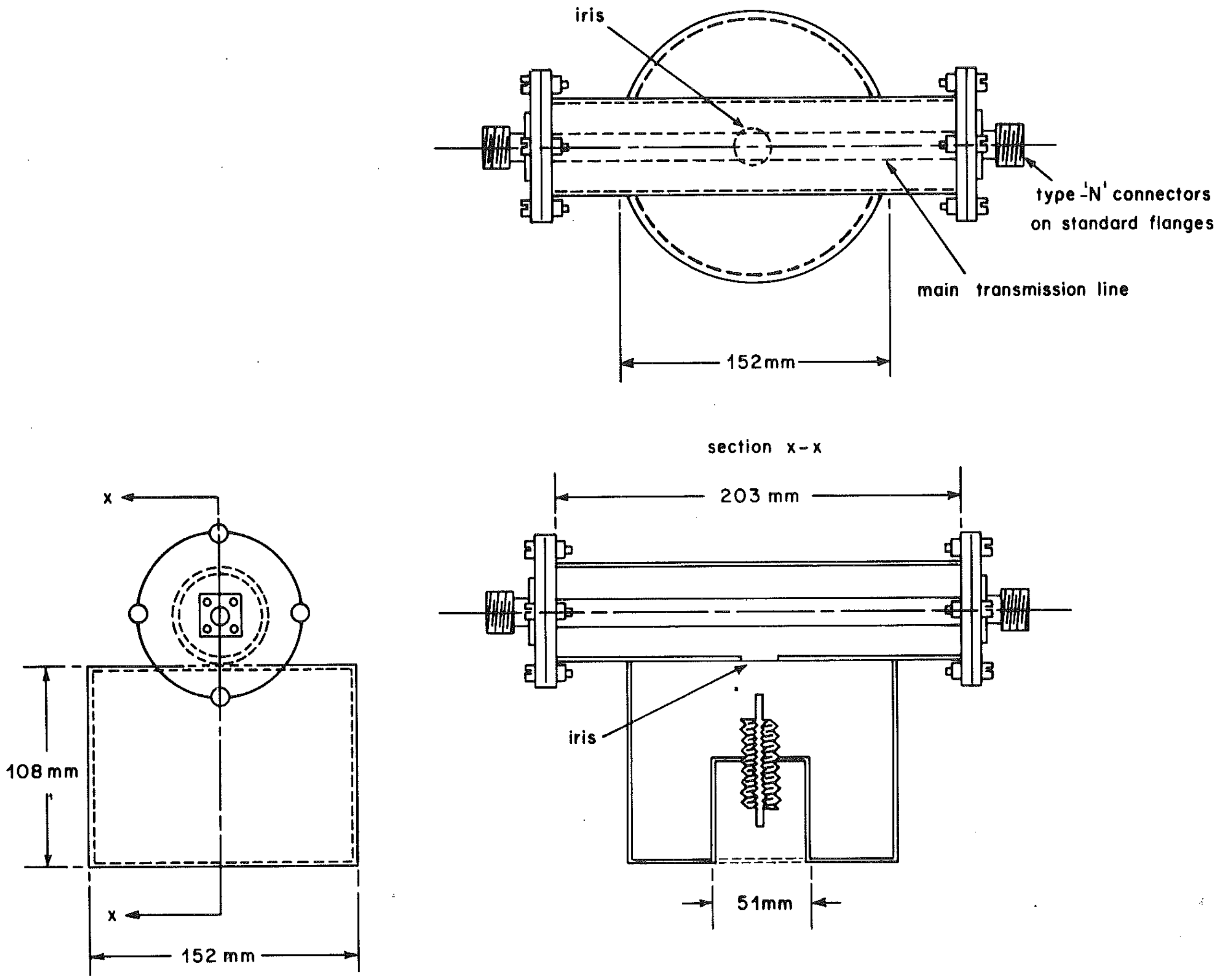

Fig. 2 - Rhumbatron band-stop filter

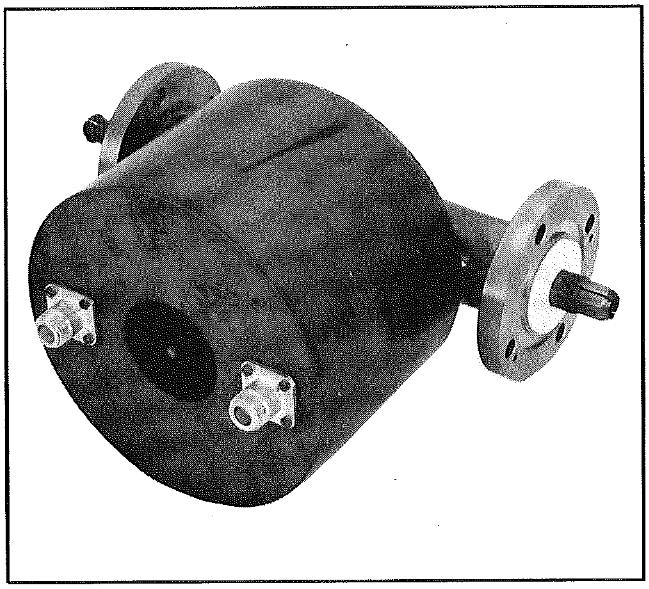

Fig. 3 - The experimental rhumbatron

across it, the observed Q_L will be low owing to the very tight coupling. In a practical resonator the degree of coupling must be controlled in order to obtain a suitable value of Q_L and coaxial resonators may be classified according to the type of coupling, namely, tapped stub, impedance transformer or capacity.

3.1. Tapped-stub resonators

This type of resonator has been used extensively at v.h.f. and detailed design procedures have been derived.[6] The resonator is defined by a stop-frequency and a pass-frequency, which are usually closely spaced, and by the required stop and pass losses. The form of construction is shown in Fig. 4(*a*). A resonator was designed for a stop loss of 30 dB at 465·25 MHz and a pass loss of 0·25 dB at 471·25 MHz, these values being chosen to be consistent with the use of 41·3 mm ($1^5/8$ inch) diameter copper feeder. The values of line length required in terms of the stop frequency are:

$$\theta_1 = 85^\circ$$

$$\theta_2 = 5{\cdot}5^\circ$$

$$\theta_3 = 55^\circ + 90^\circ$$

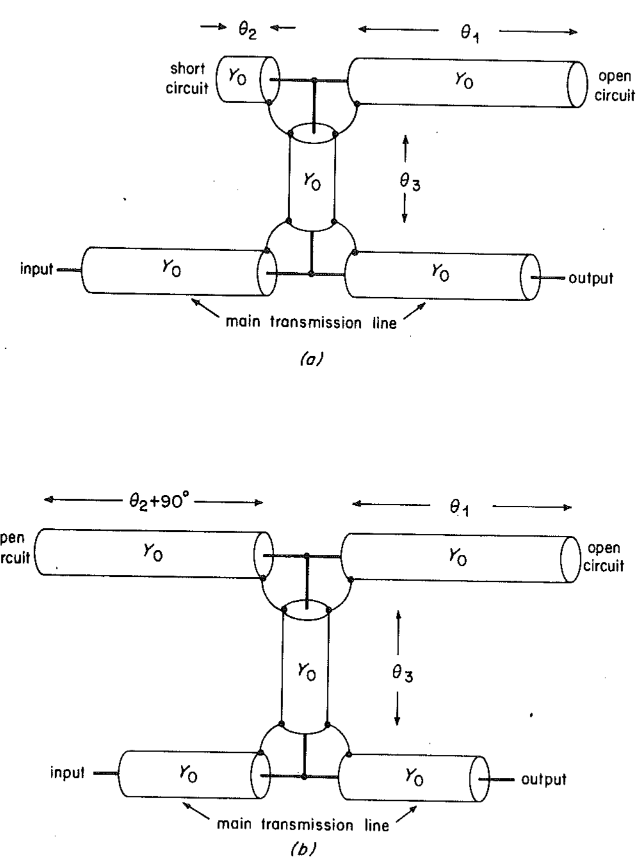

Fig. 4 - Schematic arrangement of tapped-stub resonators

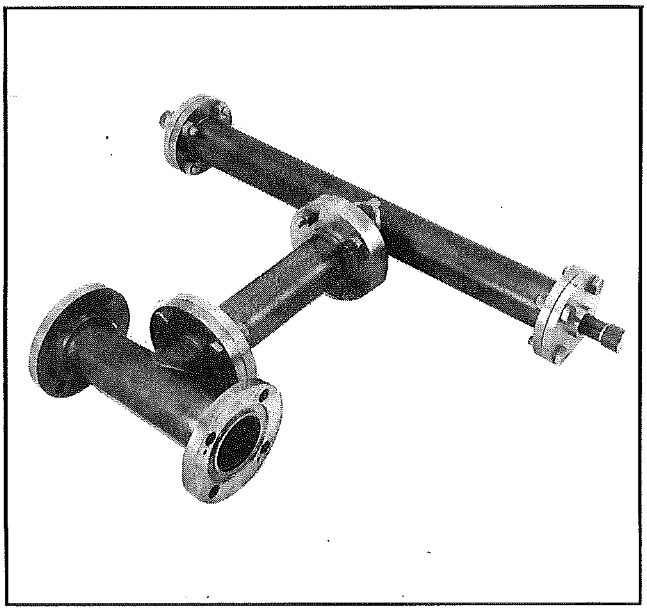

Fig. 5 - The tapped-stub resonator

θ_2 was rather short to obtain with any precision in a large diameter line and it was thought likely that some adjustment would be necessary. Accordingly the experimental model was made with an additional quarter-wavelength section and an open circuit as shown in Fig. 4(*b*). Both open circuit ends were provided with capacity trimmers so that both θ_1 and θ_2 could be adjusted. A photograph of the arrangement is shown in Fig. 5.

As made, the filter could not be tuned to a frequency higher than 459 MHz but in Fig. 6, which shows the measured amplitude response of the filter, the frequencies have been scaled up to the design requirement.

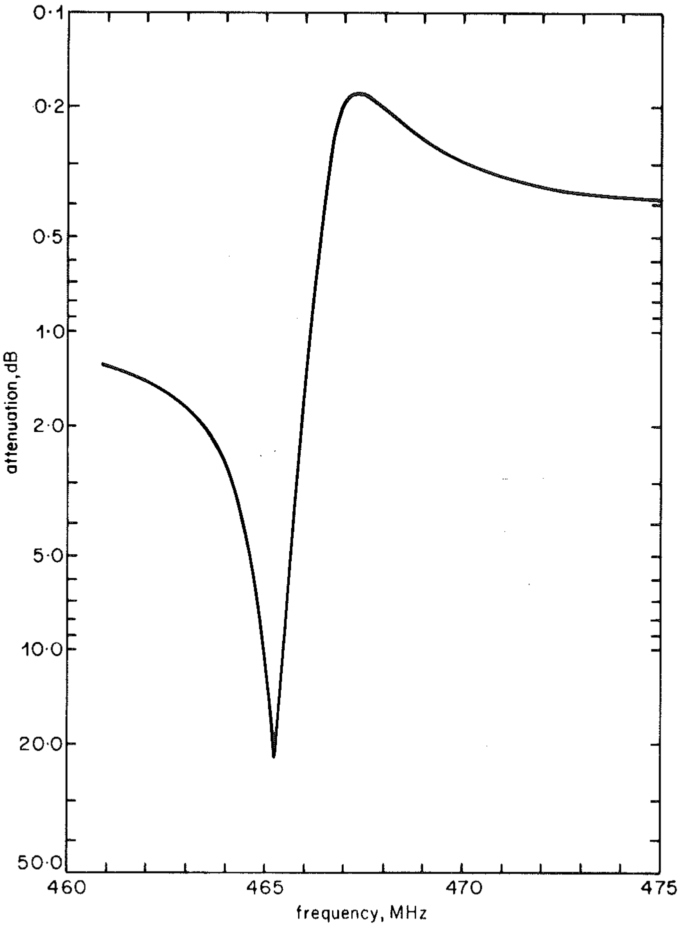

Fig. 6 - Measured attenuation of the tapped-stub filters

Although fairly compact some two or three units would be required to obtain the desired attenuation and this would make a rather heavy and cumbersome unit.

3.2. Impedance-coupled resonators

This type of resonator is mentioned here for completeness, since it is in operational service.

A satisfactory combination of pass-band and stop-band losses may be obtained in theory by using a resonant line of very high characteristic impedance (of the order of 800 ohms) but such an impedance is wholly impracticable. An equivalent arrangement may be obtained by using a line

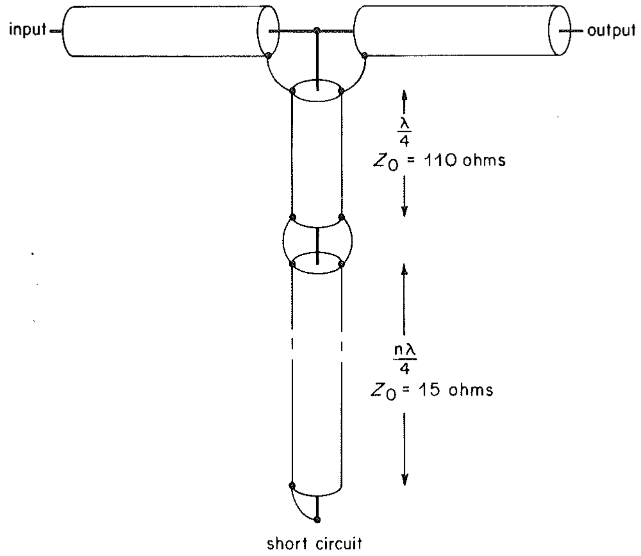

Fig. 7 - Schematic arrangement of the impedance coupled half-wavelength resonator

of very low characteristic impedance (15 ohms) transformed through a quarter-wavelength section of high impedance line (110 ohms) as shown in Fig. 7. This resonator is of necessity longer than a quarter-wavelength and it may be desirable for reasons to be described later (see Section 6) to use a low-impedance section several quarter-wavelengths long, that is, a long-line resonator.[7,8]

Resonators of this type may be made in coaxial or strip-line form.[9] A single resonator will give a stop-loss of about 24 dB but several resonators may be used in combination to give higher attenuation. A disadvantage is the length of the long-line resonators.

3.3. Capacitively-coupled half-wavelength resonators

The resonator is a coaxial or strip-line which is slightly less than a half-wavelength long at the stop-frequency and which is coupled into the main line by a small capacity.[9] The arrangement is shown in Fig. 8. The coupling capacity can be a small air-spaced trimmer but is often more easily provided by the capacity between the end of the inner conductor of the resonant line and the inner conductor of the main line; the value of the coupling is then controlled by the position of the inner conductor of the resonant line. Similarly, control of the frequency of resonance may be provided by a trimming capacity at the other end of the resonant section.

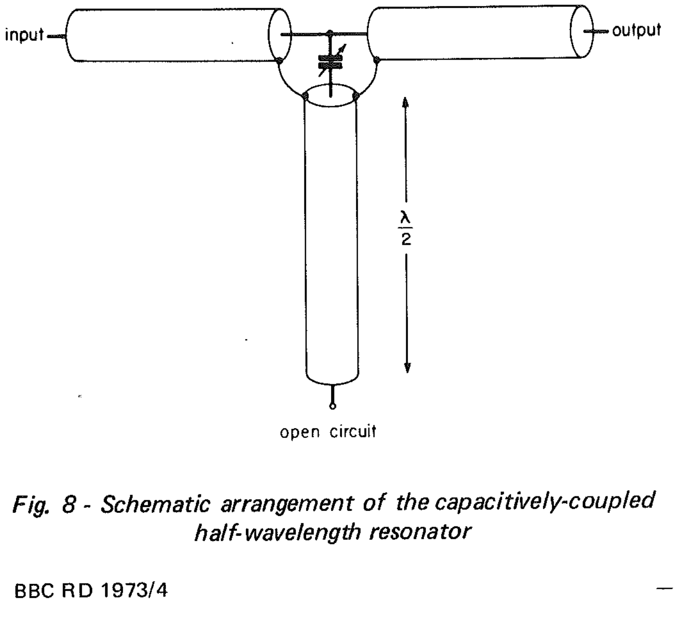

Fig. 8 - Schematic arrangement of the capacitively-coupled half-wavelength resonator

An experimental resonator was constructed using a copper outer conductor of diameter 47·6 mm and a copper inner conductor of diameter 11·1 mm and length 279 mm supported by a minimum of low-loss dielectric. The characteristic impedance of the resonator (87 ohms) was chosen to be near the condition for minimum loss.[10] Fig. 9 shows the measured frequency response of the resonator with coupling capacities of 0·5 pF, 0·7 pF and 0·9 pF.* The corresponding values of Q_L are of the order of 2,000 – 4,000. A change to the coupling capacity also changes the resonant frequency; this effect has been corrected in Fig. 9.

As well as being reasonably compact and easy to set up, this type of resonator can be used with a number of units in cascade.

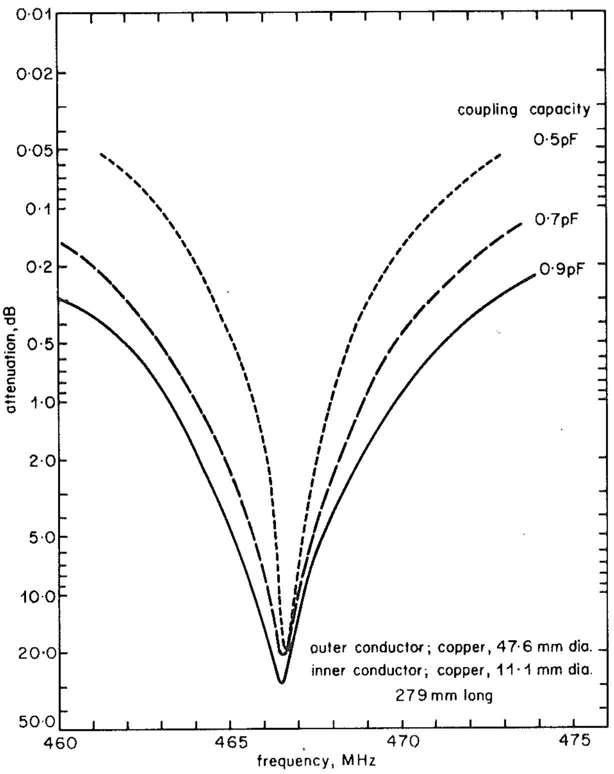

Fig. 9 - Attenuation of single half-wave resonator with various coupling capacities

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* These capacities were measured directly using a transformer radio-arm bridge capable of measuring small capacities in the presence of much larger common capacities to ground.[11]

4. Multi-resonator filters

It has been shown above that a stop-loss of about 20 dB and a $Q_L > 1000$ can be obtained from a single resonator. If much higher stop-losses are required while maintaining a high Q_L, a number of resonant elements must be used together. It may be shown that if a number of shunt-connected resonators are distributed along a transmission line at intervals of one quarter wavelength, or a multiple thereof, it is possible to simulate a ladder network of alternate series and shunt elements.[2] The result, often called a 'quarter-wave coupled filter' is a simple and effective design which has been studied in some detail.[2,3]

All of the types of resonator described above can be cascaded in this manner; however the rhumbatron would need coupling lines at least three-quarter wavelength long so that the complete filter would be rather bulky.

5. Other considerations

The filters considered so far have been the simplest types that are capable of giving the required pass and stop losses. In practice, other considerations may arise. Two which are of particular interest with television transmitters are the use of constant impedance networks and considerations of group delay.

5.1. Constant impedance networks

This class of network presents a constant impedance over the pass and stop-bands, that is, energy entering the network at frequencies in the stop-band is diverted to a resistive load rather than be reflected back to the source.[12] A second advantage is that the attenuation is not dependant on the terminating impedance so that the performance is more predictable. Such an arrangement is valuable for a filter fitted to the output of a transmitter having source impedance that is not well-matched to the feeder (e.g. a klystron).

A constant-impedance network may be achieved by connecting a pair of hybrids back-to-back as shown in Fig. 10. The lines connecting the two hybrids are each fitted with a multisection filter; these filters are, in general, displaced by a distance *d* which depends upon the type of hybrid used. Thus a split-drum hybrid, which gives co-phased outputs, would require $d = \lambda/4$ whereas a 0 dB directional coupler giving quadrature outputs requires $d = 0$.

5.2. Group delay

A filter tuned to a frequency near to a television channel will produce a variation of group delay across the channel and, if this variation is too great, degradation of the picture quality will result.

The overall delay characteristic was originally specified[13] to be ±60 ns over the greater part of the video band with a tighter tolerance in the vicinity of the colour subcarrier but there is as yet no agreed international standard.[14] An estimate of the probable maximum contributions from the different parts of the transmission chain[15] suggests that 55 ns variation over the video band is likely to be found in a re-broadcast transmitter. Thus it is not possible to specify the maximum permissible group delay with any certainty but it is probable that the delay inequality between luminance and chrominance components is the most important consideration and that this should not exceed about 40 ns. It might be possible to relax this requirement for small relay stations.

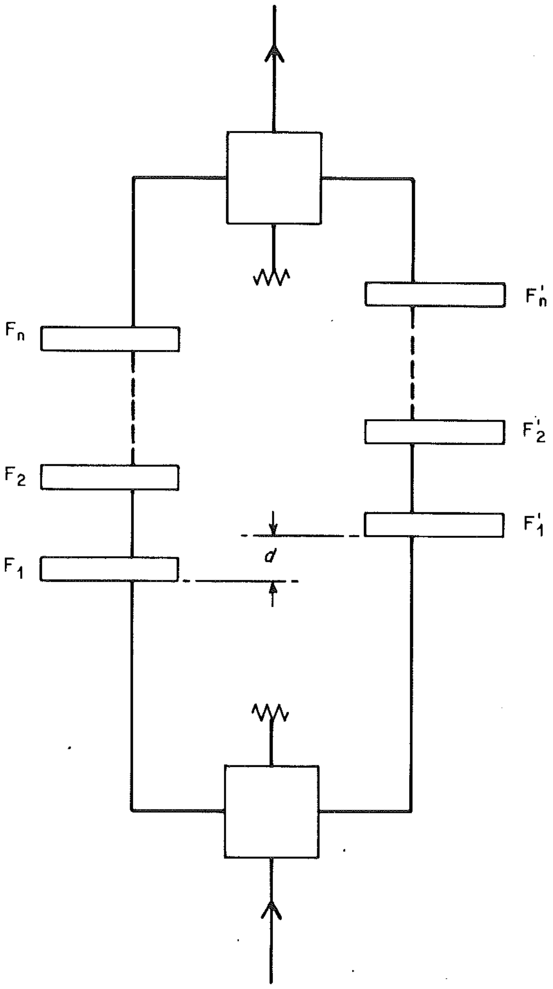

Fig. 10 - The constant impedance network

6. The long-line filter[8]

This consists basically of an array of three resonators, two being tuned to the image sound frequency (465·25 MHz) and one to the image colour-subcarrier frequency (466·82 MHz). The filter was constructed in constant impedance form so that double this number of resonators is actually used (Fig. 11). Each resonator is as described in Section 3.2 above and is the long-line form having high attenuation at each frequency at which it is an odd number of quarter wavelengths long. This has the advantage that the length can be chosen to give a second region of high attenuation above the pass-band so that the variation of group delay over the pass-band is minimised.[7] The overall

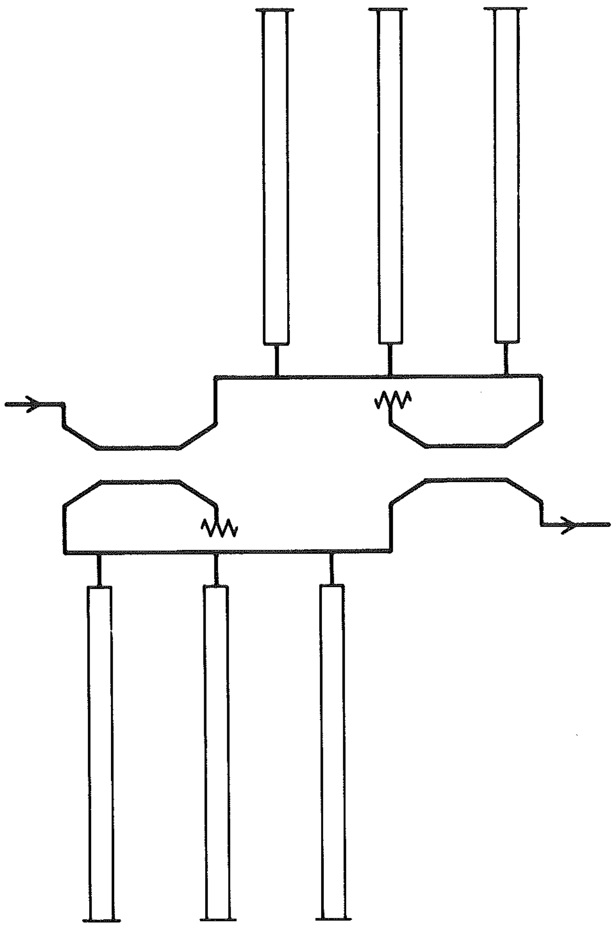

Fig. 11 - General arrangement of long-line filter

dimensions of the unit are approximately 2,000 mm x 700 mm x 160 mm.

Fig. 12 shows the attenuation and Fig. 13 the group-delay of this filter, reproduced from Reference 10. The delay inequality between vision carrier and colour sub-carrier is 53 ns. An examination of the radiated picture quality at site did not reveal any great degradation attributable to the filter but viewing conditions were less than ideal.

6.1. The prototype filter

A prototype filter was constructed with six half-wave resonators arranged in pairs on a 22·2 mm square rigid coaxial line as shown in Fig. 14. The resonators are coupled to this line by the small capacity of the end and trimmers are provided at the other ends for turning. It was thought that it was probably not necessary to make the filter in constant impedance form since it was designed for use with travelling-wave tube amplifiers which have a reasonably well-matched output impedance.

The initial design was carried out using the curves of Reference 16. The target specification was for a stop-band loss of 35 dB over a 0·5 MHz bandwidth centred on either 465·25 MHz or 466·82 MHz and a pass-band loss of 0·3 dB over a 5 MHz bandwidth. It appeared that this could be

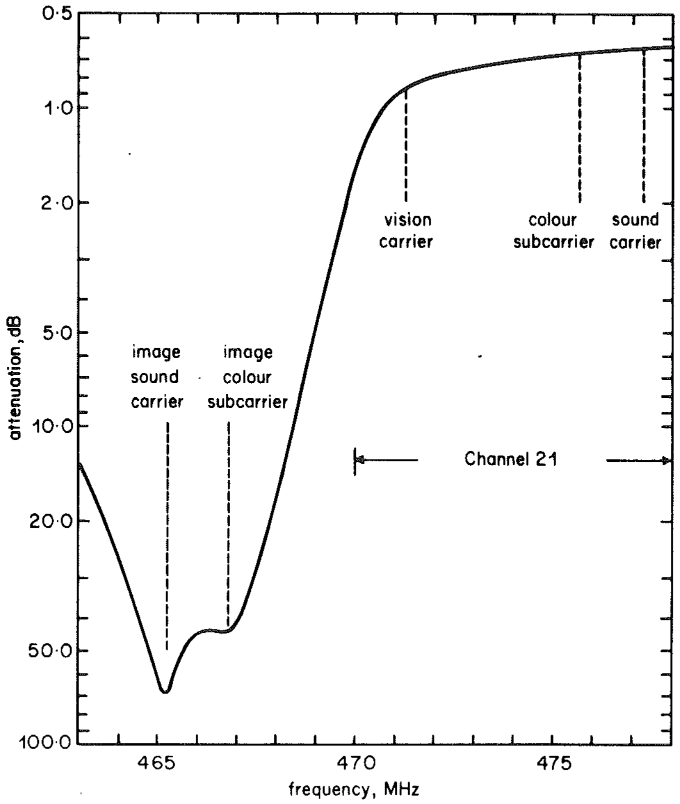

Fig. 12 - Attenuation of long-line filter

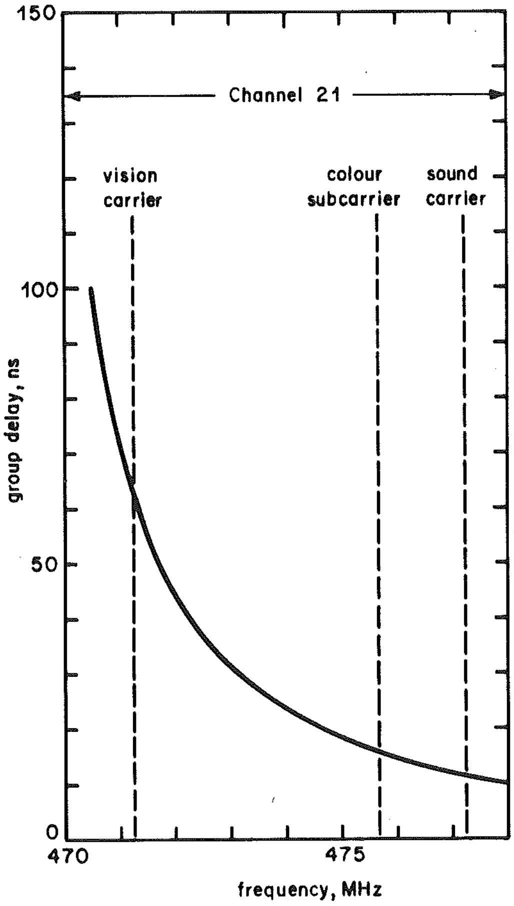

Fig. 13 - Group delay of long-line filter

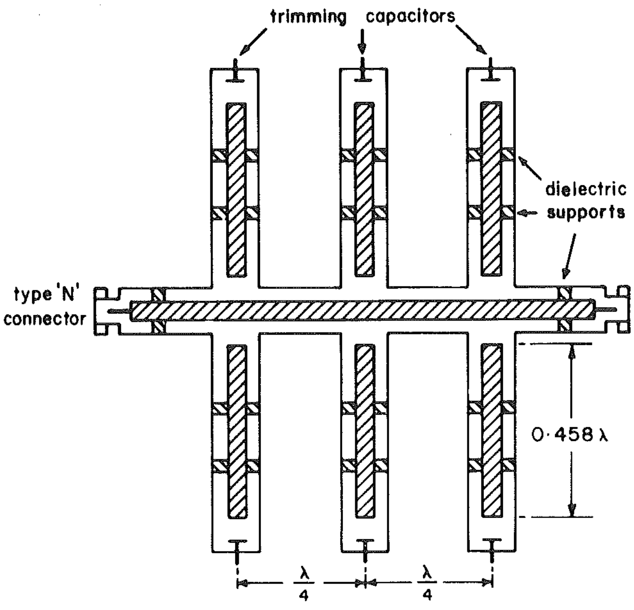

Fig. 14 - The prototype half-wave resonator filter

met with three resonators on each frequency using line elements having a reasonably low value of Q_u (1330). The length of the inner conductors was found to be 0·458λ and the required value of coupling capacity to be 0·69 pF.

The design was checked by using a computer programme to evaluate the amplitude and group-delay responses. It was assumed that three half-wave resonators were on a frequency of 465·25 MHz, each with a coupling capacity of 0·7 pF, and three resonators on a frequency of 466·28 MHz with a coupling capacity of 0·65 pF. All line sections were assumed to have a loss of 0·02 dB per wavelength (Q_u = 1364). The computed attenuation is shown in Fig. 15 where it is compared with the measured attenuation of the prototype. There is some divergence at the edge of the pass-band, where it is difficult to measure the small attenuation involved, and the maximum attenuation is calculated to be greater than that obtained in practice, probably because the resonators on each frequency were not absolutely identical, but in general the agreement is good.

The computed group delay is shown in Fig. 16; the maximum variation over the pass-band is 89 ns and the

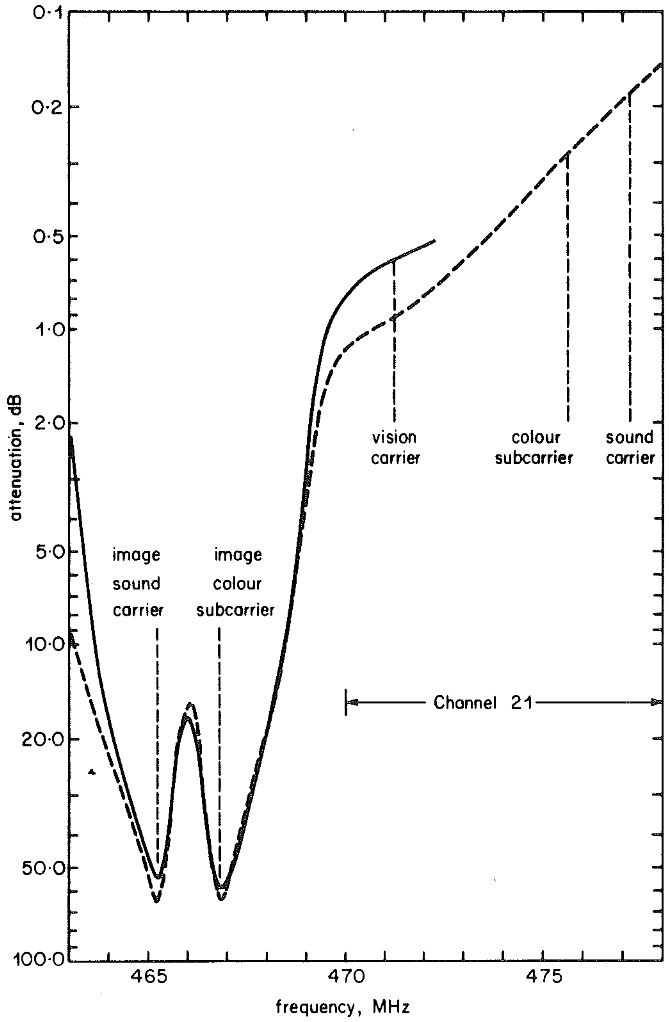

Fig. 15 - Attenuation of prototype half-wave filter

– – – – Measured ——— Calculated

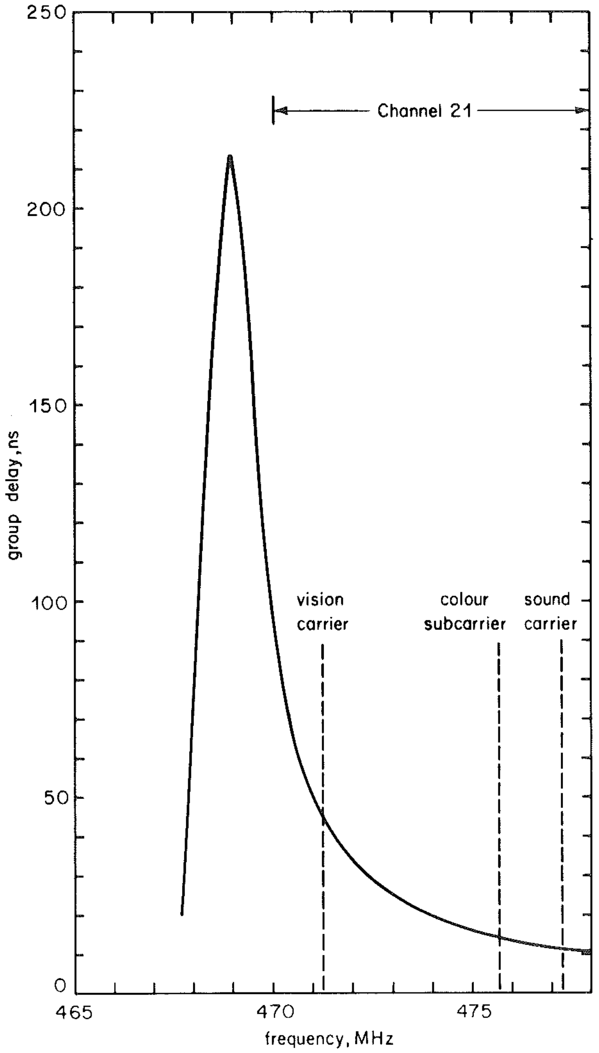

Fig. 16 - Group-delay of prototype half-wave filter

difference between vision carrier and colour subcarrier is 30 ns. As explained in Section 5.2 it was not clear at the outset what additional group-delay variation could be tolerated and some consideration was given to improving the performance in this respect. It was found that if the coupling to the 466·82 MHz resonators was reduced so that the total attenuation at this frequency was only about 50 dB, the total variation of group-delay across the pass-band was brought down to 51 ns.

6.2. Stability considerations

In service use a transmitter filter may be subject to temperature cycling of as much as 35°C. For a copper line this corresponds to a frequency shift of about 0·25 MHz which would be quite unacceptable in the present application. Apart from the change in length of the resonator the values of the small capacities at each end will also change and this may be used to effect some compensation. The outer conductor of the resonator is made of brass which has a slightly greater coefficient of expansion than copper, which is used for the inner conductor. As the resonator is heated the inner conductor increases in length but the greater expansion of the brass outer conductor succeeds in reducing the coupling capacity. The two effects may be equalised by proper choice of the area of the end of the inner conductor. The small trimming capacity at the outer end of the resonator may be treated similarly.

6.3. The final model

The experience used on the prototype filter was taken into account in the construction of a final model suitable for service use. Although it had been shown that three resonators on each frequency provided as much attenuation as was believed to be necessary, it was decided that it would be prudent to make the final version with two extra resonators; these could be used to provide extra attenuation on the principal interfering frequencies or on some other frequency or to reduce the variation of group delay across the band. The main line was constructed of standard EIA $1\,^5/_8$ inch (41·3 mm) 50 ohm rigid line (copper inner, brass outer) with flange connectors[17] since this suited the transmitter installation. The resonator arms used a 22·2 mm ($^7/_8$ inch) brass outer conductor and a 6·4 mm (¼ inch) copper inner conductor corresponding to a characteristic impedance of 75 ohms; ideally this should be near the value for minimum loss with the materials in question, but it is not critical.[10] A photograph of this filter is shown in Fig. 17; the overall dimensions are 600 mm x 632 mm x 9 mm. Fig. 18 shows an amplitude response with four resonators tuned to 465·25 MHz and four tuned to 466·82 MHz.

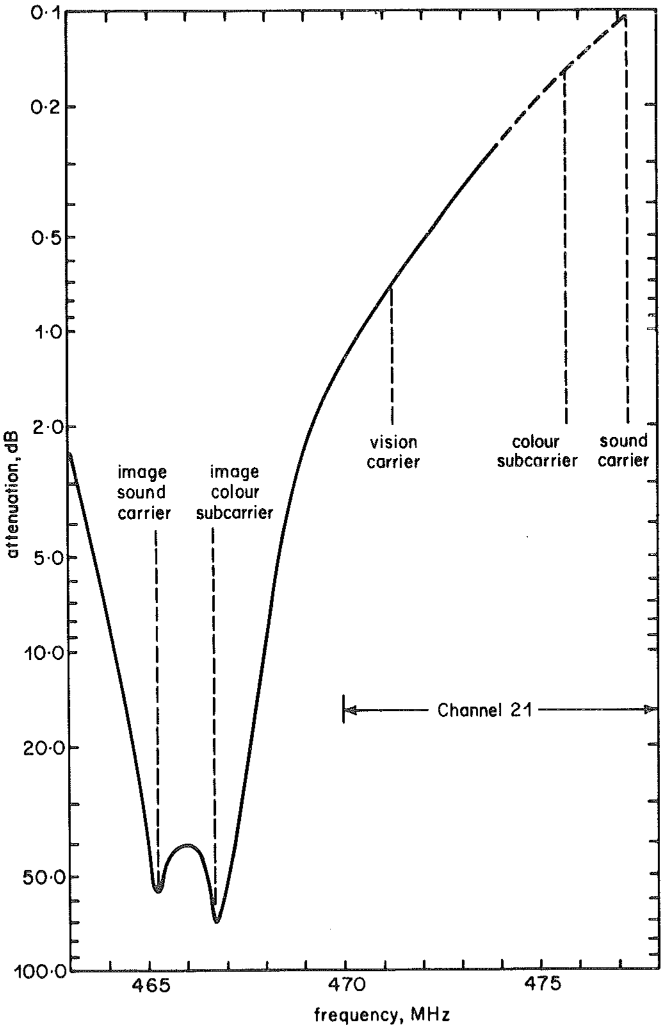

Fig. 18 - Attenuation of eight-resonator half-wave filter

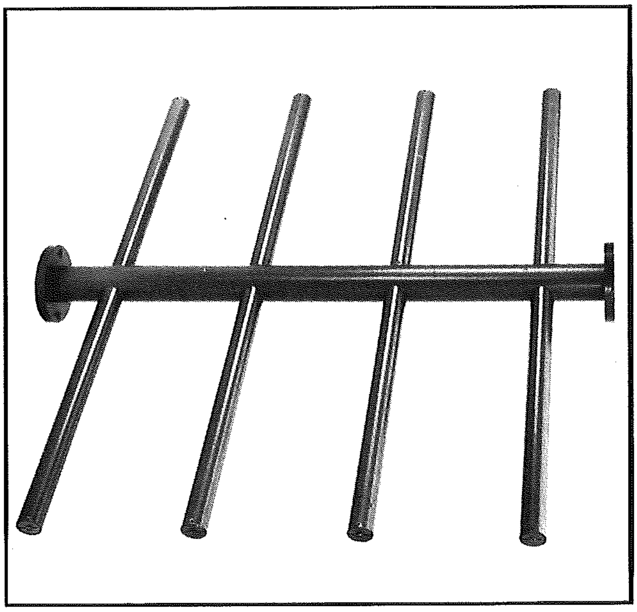

Fig. 17 - The eight-resonator half-wave filter

This filter was taken to Halifax for the tests referred to earlier but was not required for service as the long-line filter satisfied the immediate requirements.

7. Low-power strip-line filters

In addition to the transmitter filters discussed above, there was a requirement in the tests at Halifax for a number of low-power filters. These were to be fitted to the inputs of base-station receivers used in conjunction with mobile transmitters to attenuate the television signal and so ensure that the interfering signals were not generated by intermodulation in the input stages of the receivers. It was thought that a stop-loss of 25 – 30 dB at the vision-carrier frequency of 471·25 MHz would be adequate for this purpose. In addition it was desired that the pass-band loss in the region of 465·25 MHz should be reasonably low.

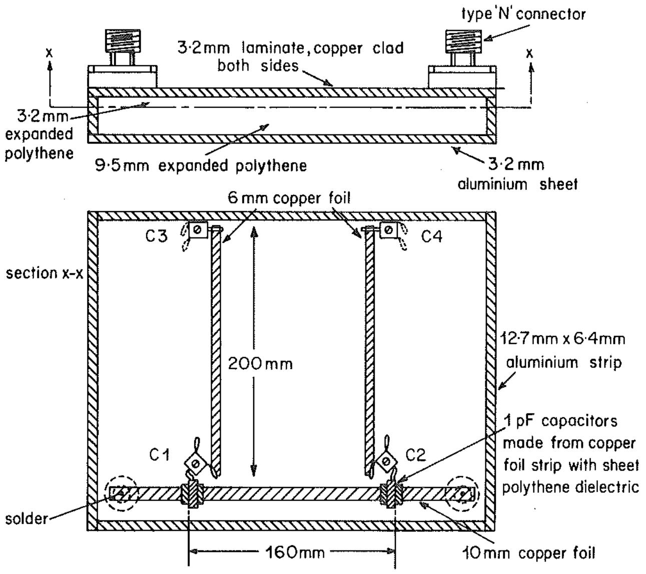

Fig. 19 - Low-power strip-line filter

It was decided to use two half-wave resonators in a strip-line sandwich construction.[18] Fig. 19 shows the arrangement. The half-wave resonant lines consist of 6 mm wide copper strips sandwiched between layers of expanded polystyrene. The half-wave resonators are coupled to the main line by means of a 1 pF fabricated capacity in series with a small trimmer from which some of the vanes had been removed. Additional trimmers are fitted to the other end of the resonators for tuning and access to these is provided by holes in the outer plates. The overall dimensions are 229 mm x 229 mm x 45 mm.

Four of these filters were made and used in the course of the Halifax tests for eliminating intermodulation in the measuring equipment and in the base station equipment. A typical amplitude response is shown in Fig. 20.

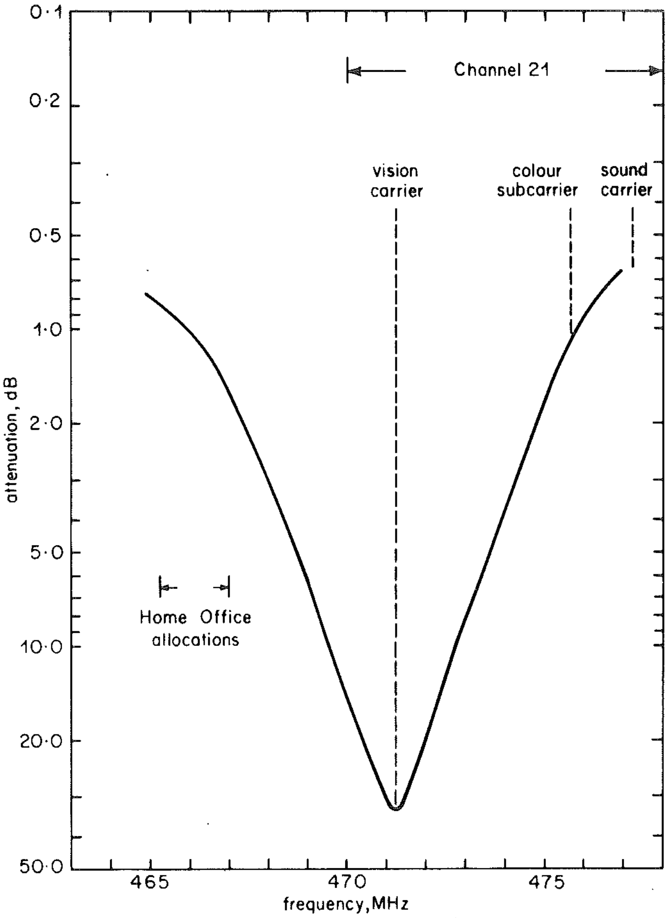

Fig. 20 - Attenuation of strip-line filter

8. Conclusions

The principal object of the work was to provide a reserve filter for a particularly important experiment and this was completed successfully. The design produced, based on the half-wavelength resonant line, differs from that currently in use in being appreciably less bulky; this could be an important advantage at low-power relay stations where space is at a premium.

It is thought that for transmitters having a good output impedance (this includes all the types currently in use for peak vision output powers of 200 W or less), it will not be necessary to use a constant impedance filter. Confirmation of this point is desirable since it would bring a considerable simplification of the installation at a station using Channel 21.

One further aspect which is in need of elucidation is the extent to which the group delay may be permitted to vary over a television channel, particular attention being given to the large variation that can occur in the region of vestigial sideband.

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